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Aaron Flood

Frank W. Liou
Missouri University of Science and Technology, liou@mst.edu

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EFFECT OF ENVIRONMENTAL VARIABLES ON TI-64 AM SIMULATION RESULTS

Aaron Flood* and Frank Liou*

*Department of Mechanical and Aerospace Engineering, Missouri University of Science and Technology, Rolla, MO 65409

Abstract

In metal AM the environment is critical and therefore care should be taken to ensure that the simulation matches reality. This paper will investigate the effect that various environmental factors have on the results of the simulation. This will help to determine their importance in the simulation setup. The material properties which relate to this are the convective coefficient and the emissivity. These material properties will be investigated to determine their effect on the outcome of the simulation. In addition to these properties, the size of the substrate will be investigated to determine if any results are altered. Lastly, the ambient temperature will be investigated to determine the effect this has on the simulation results.

Introduction

With the expense that is associated with additive manufacturing (AM), especially metal AM, in recent history many mathematical models [1, 2, 3, 4] have been developed to facilitate faster and cheaper understanding of the process. In order to properly simulate the process of AM, several assumptions and shortcuts need to be taken in order for the simulation to complete in an acceptable amount of time. An example of the use of shortcuts is to use static material properties instead of temperature dependent properties. These assumptions and shortcuts can have a significant impact on the results of the simulation. This study investigates the effect of surface material properties, ambient temperature, and substrate size on the temperature distribution on the surface of the specimen. The software used to run the simulation is the Additive Manufacturing Simulator (AMS). This software is being developed in a joint effort between Missouri University of Science and Technology and Product Innovation and Engineering, LLC. This software is an efficient physics based simulation solution focusing on metal additive manufacturing.

For all of the simulations which are performed a base set of parameters was used. These are listed in Table 1. It was determined that parameters of emissivity and convective coefficient are so closely coupled that they should be investigated together, whereas the parameters of ambient temperature and substrate size were independent and could be investigated on their own. In order to quantify the differences in the simulation results, a contour plot of the surface temperature was created for each simulation, an example of this can be seen in Figure 1. These contour plots were then analyzed to determine the number of voxels which were above a range of temperatures. A range of temperatures was used in order to avoid a bias which could have occurred if only a one or two temperatures were used. These results were then processes using SAS in order to determine any statistical differences.

Table 1: General parameters used for all simulations

Material	Ti-64
Laser Diameter	3.0 mm
Laser Power	1000 W
Laser Distribution	Top Hat
Laser Scan Speed	5 mm/sec
Resolution	750 μm
Emissivity	0.4 W/m^2
Convective Coefficient	5.0 W/m^2K
Ambient Temperature	298 K
Substrate Size	1.5 cm x 1.0 cm x 0.75 cm

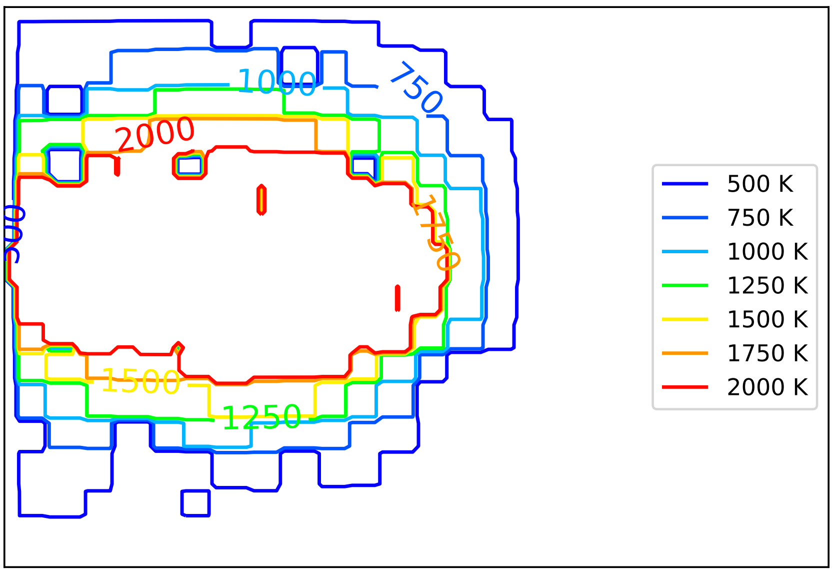


Figure 1: Sample contour plot of surface temperature

Material Properties Effect

One of the most important aspects to any simulation is gathering the correct inputs. In the case of AM simulation, the material properties can be some of the most important and challenging to find. This set of simulations will focus on the effect of the convective coefficient and emissivity on the temperature distribution of the surface of a part. The values which were used as the base values in the design of experiment (DOE) can be seen in Table 2. These values were found to be a good representation of the wide range of values that can be found throughout literature.

In order to realize the goal of determining their effect, the values needed to be varied by a substantial amount. For the emissivity, the constraint of the value needing to be between 0 and 1 was included and for the convective coefficient, the constraint of needing to be greater than or equal to 0 was added. With this constraint the values chosen can be seen in Table 3. This range of parameters resulted in the need for 10 experimental runs to determine the effect that each has on

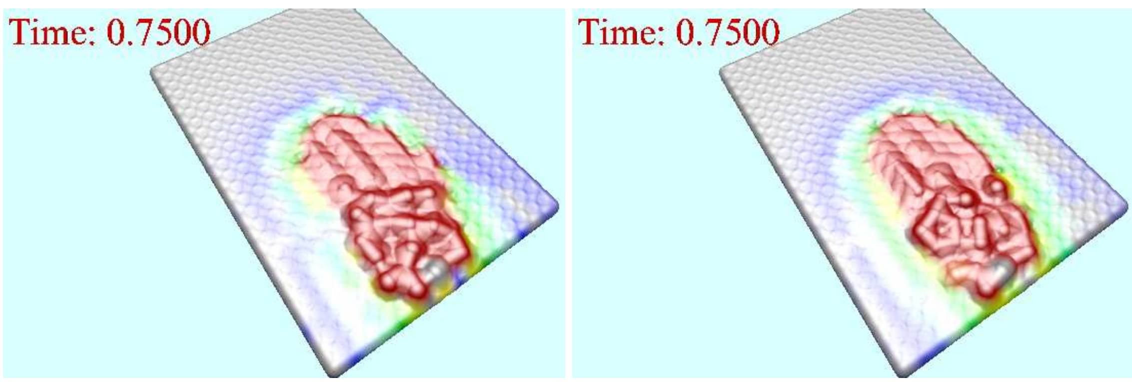
Table 2: Values found in literature

Property	Value
Convective Coefficient	5.0 [2]
Emissivity	0.4 [5]

Table 3: Values used in material property investigation

Property	High Value	Base Value	Low Value
Emissivity	0.9	0.4	0.1
Convective Coefficient	7.5	5.0	2.5

the results. A sample of the temperature distribution which resulted from the simulations can be seen in Figure 2.



(a) Simulation number 2

(b) Simulation number 0

Figure 2: Sample images from material properties simulations

From the images collected, the contours were produced and the raw data was collected and can be seen in Table 4. These results were then analyzed to determine the ability of these two

Table 4: Raw data collected for material property simulation

Sim. Num.	Conv. Coef. (p-value)	Emis. (p-value)	500°K	1000°K	1500°K	2000°K	2500°K	2995°K
0	2.5	0.1	3525	2395	1880	1464	1383	1379
1	2.5	0.4	3525	2395	1880	1464	1383	1379
2	7.5	0.1	3545	2265	1831	1523	1489	1489
3	5.0	0.4	3532	2396	1793	1391	1294	1284
4	5.0	0.4	3532	2396	1793	1391	1294	1284
5	2.5	0.9	3525	2395	1880	1464	1383	1379
6	7.5	0.4	3545	2265	1831	1523	1489	1489
7	5.0	0.1	3532	2396	1793	1391	1294	1284
8	5.0	0.9	3532	2396	1793	1391	1294	1284
9	7.5	0.9	3545	2265	1831	1523	1489	1489

parameters to predict the surface temperature distribution. The p-value of the model is reported in Table 5. As can be seen from the p values reported, the model is a good fit for the data, meaning

Table 5: Statistical model analysis of material property results

Temperature	Model P Value
500	$< .0001$
750	$< .0001$
1000	$< .0001$
1250	$< .0001$
1500	$< .0001$
1750	$< .0001$
2000	$< .0001$

that the parameters of convective coefficient and emissivity have a statistically significant effect on the temperature distribution on the surface of the part. Next, the effect that each parameter has on the model was investigated. The results can be seen in Table 6. This statistical analysis agrees with

Table 6: Statistical analysis of variables for material property experiments

Temperature	Conv. Coef.	Emis.
500	$< .0001$	0
750	$< .0001$	0
1000	$< .0001$	0
1250	$< .0001$	0
1500	$< .0001$	0
1750	$< .0001$	0
2000	$< .0001$	0

the results which can be observed in the raw data in Table 4, namely that changing the emissivity does not affect the temperature distribution of the surface of the part. In the raw data, this can be illustrated with simulation runs 0 and 1. In these simulations, the convective coefficient is kept constant and the emissivity is changed, however, the results are identical. In the statistical analysis, this inference can be drawn from the p-value of emissivity being 0.

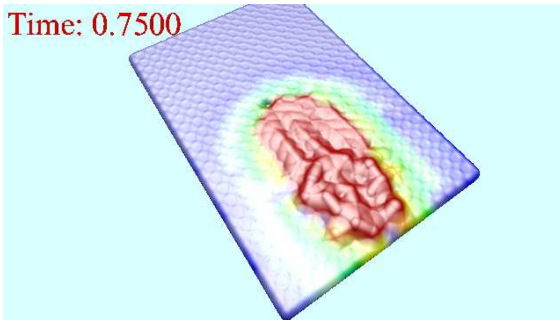
Ambient Temperature Effect

Tangentially related to the material properties is the ambient temperature of the build chamber. In order to investigate the effect the ambient temperature has on the simulation results the 4 values, listed in Table 7, were used.

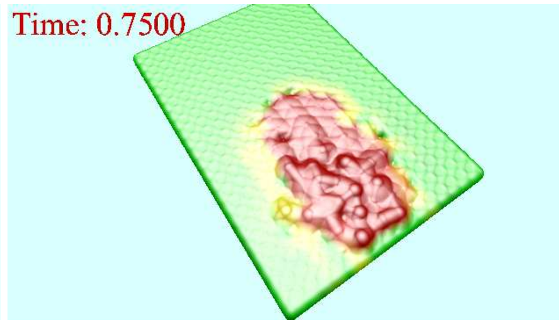
Table 7: Ambient temperatures used in simulations

Property	Temperature (in degree K)
Temperature	298., 500., 1000., 1500.

When the simulations were completed the results were collected and the images were visually compared, a representative pair of images are shown in Figure 3. The image in Figure 3a is using



(a) Simulation Number 1 (500°K)



(b) Simulation Number 3 (1500°K)

Figure 3: Sample images from ambient temperature simulations

a 500°K ambient temperature and Figure 3b is using a 1500°K. Other than the obvious difference in the substrate temperature, there is a visible difference in the melted region shown in red. When the ambient temperature is larger the melt pool also grows wider. This is also observed in the raw data which was collected and displayed in Table 8. As can be observed in this table, as

Table 8: Raw data collected for ambient temperature simulations

Sim. Num.	Amb. Temp	1750°K	2000°K	2250°K	2500°K	2750°K	2950°K
0	298.0	1584	1391	1344	1294	1284	1284
1	500.0	1669	1465	1360	1307	1304	1304
2	1000.0	1669	1463	1432	1327	1317	1317
3	1500.0	2199	1694	1545	1354	1341	1341

the ambient temperature is increased so does the number of voxels which are counted for each threshold temperature. In order to quantify these results, statistical analysis was performed by using a T-test to determine the significance of the ambient temperature on the melt pool size, these are displayed in Table 9. As can be seen, the ambient temperature has a statistically significant

Table 9: Statistical analysis for ambient temperature simulations

Temperature	Model P Value
1750	0.0011
2000	0.0002
2250	< 0.0001
2500	< 0.0001
2750	< 0.0001
2950	< 0.0001

impact on the temperature distribution of the part. Interestingly, as the investigation temperature increases so does the significance that the ambient temperature has on the surface area that is above that temperature. This effect could be an artifact of the statistics, namely a lower signal to noise ratio. In order to show this, a more detailed study must be performed.

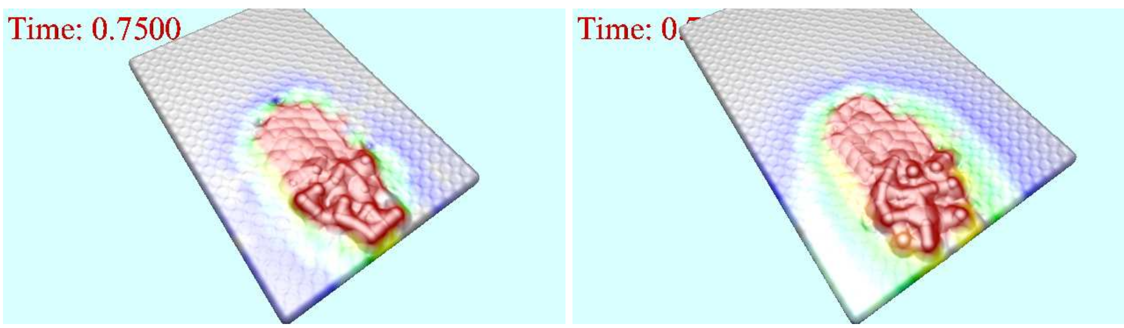
Substrate Size Effect

The final environmental variable investigated which could affect the simulation is the fixturing which is used to clamp the specimen in place. This set of simulations investigates this effect by increasing the size of the specimen. This will simulate the increased thermal mass which can be seen when additional fixturing is needed. The substrate sizes simulated can be seen in Table 10. The x and y dimensions of the specimen were increased proportionally while keeping the z dimension constant. Representative images from the simulations can be seen in Figure 4. Visually

Table 10: Substrate sizes used in simulations

x	y	z	volume
1.5	1.0	0.75	1.125
1.65	1.1	0.75	1.36125
1.8	1.2	0.75	1.62

Values (in cm or cm^3)



(a) Simulation number 0

(b) Simulation number 2

Figure 4: Sample images from substrate size simulations

inspecting the images, it can be seen that more conduction takes place in the larger part, Figure 4b, and less conduction occurs in the smaller specimen, Figure 4a. The raw data for this experiment, Table 11, shows a similar trend, namely that larger substrates results in more heat being pulled away from the melt pool resulting more voxels at higher temperatures. The exception to this trend is simulation number 1. More conduction is seen in simulation 1 than simulation number 2 which was a larger substrate. In order to understand this phenomenon, more investigation is necessary. To quantify the statistical significance of the raw data, a T-test was performed on the data, which

Table 11: Raw data collected for substrate size simulations

Sim. Num.	Volume	500°K	1000°K	1500°K	2000°K	2500°K
0	1.125	2804	1851	1539	1308	1304
1	1.36125	4021	2810	2175	1670	1415
2	1.62	4120	2875	2084	1596	1368

resulted in the data in Table 12. As can be seen from the p-values, the model is a good predictor of

Table 12: Statistical analysis for substrate size simulations

Temperature	Model P Value
500	0.0132
750	0.0193
1000	0.0169
1250	0.0114
1500	0.0104
1750	0.0056
2000	0.0052

the temperature distribution within the specimen. An interesting trend that can be seen in the data is that as the temperature is increased the p-value decreases. This shows that the substrate size is more critical to the temperature distribution at higher temperatures.

Conclusion

Several conclusions can be drawn from the simulations which were performed in this presented work which correlate the sensitivity of the temperature distribution to various environmental parameters. The first investigated were the emissivity and convective coefficient. It was seen that the simulation is sensitive to the input of the convective coefficient and not emissivity. When investigating the effect of ambient temperature, it was found that the ambient temperature has a statistical influence on the temperature distribution within the specimen. And lastly, it was seen that the substrate size has a significant impact on the temperature distribution of the specimen.

During the course of these simulations, several new questions were raised. In order to investigate these questions, several future steps have been identified. First, the simulations will be performed at a higher resolution. This will identify effects that are particular to this resolution selection and ones which can be applied generally to the simulation. Along the same line of investigation, the software allows for a dynamic resolution which will allow for a more detailed investigation of the melt pool area. In addition, the effects that these parameters have on the melt pool depth would like to be investigated. Lastly, the effect that various parameters have would like to be experimentally validated to ensure that the simulation results match reality.

Acknowledgments

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